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This work reports on converting carpet waste directly into durable underlays (pads) using co-polymer mixtures and high temperature curing. Its performance in comparison with three commercially available underlays will be discussed.

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ABSTRACT

Currently a large proportion of carpet waste destined for landfill is made up of pre-consumer or process waste in the form of selvedge edging, mismatches and substandard and faulty carpets. In Europe, these types of waste account for 1.6 million tonnes of all waste dumped into landfill. In the UK alone, 90% of all fibrous wastes are carpet-related waste and in the Northwest, where land is particularly scarce, there are only four years of licensed landfill space available. There is therefore an urgent need to address waste dumping in general and carpet waste in particular.

This work reports on converting carpet waste direct into durable underlays using co-polymer mixtures and high temperature curing. The novel underlay is then tested and compared with three commercially available underlays of similar physical characteristics according to British Standard routines. The testing protocol includes cracking /breaking, dynamic loading, breaking strength and elongation as well as tear strength. The novel underlay is subsequently assessed and further optimisations are carried out with respect to waste particle size, underlay thickness and resin composition.

1.0 INTRODUCTION

Combining acceptable aesthetic qualities as well as durable and mechanical properties, floor coverings are produced on a grand scale. In Western Europe the collective quantity of floor coverings produced exceeds 900 million m^2 [1]. Such high production rates create varying percentages of waste, which in turn contribute to the 4 million tonnes of waste generated annually in the UK [2].

Throughout Europe, around 1, 600,000 tonnes of carpet are disposed of every year, an area equivalent to 57,000 football fields [3]. The net effect is that the cost of disposal is rising steadily and currently in the UK it stands at £65 per tonne [4]. However, in the UK [5] the consumer still perceives waste disposal as being free.

Reliance upon landfill is one of the major issues associated with waste management and increasingly challenges the floor covering industry to take an active role in developing processes to comply with environmental regulations. Concentrating on methods at the top of the hierarchy i.e. landfill. One major disadvantage associated with landfill is the limited reserves.

The question of 'what to do with waste' has attracted huge funding in the recent past for example including the use of tyre scrap into underlay products. Although a successful process in its own right, it does not alleviate the mounting quantity of carpet waste produced. At present the established methodologies include pyrolysis or burning in the absence of oxygen or incineration with prime purpose of recovering the locked in energies [6]. Granulation, shredding or mixing the waste with binders to produce end products are other schemes of utilisation currently in practice. The underlying factors limiting full development of these methods are the high costs of collection, sorting, cleaning and ultimately reproduction. The novel underlay proposed and researched in this work would be economical to produce, functional and long lasting.

The intention of the current research is therefore to produce a cost effective product in the form of a novel underlay by utilising recycled material in the form of production waste from carpet manufactures. The expected outcome is a product, which would conform to BS testing regimes and displays comparable if not more desirable properties than other commercial underlays.

1.1 Underlay

The fixing of carpets directly to the floor (direct stick approach) is common practice for contract installation in many countries. The laying of carpets in conjunction with separate underlay is still widely used. Hence `out of sight out of mind' [7] is the most misleading principle to apply to carpet underlay. As well as overcoming minor irregularities in the floor, underlay imparts excellent cushioning effects with increased insulation. Over a reasonable period of use [8] there should be no great change in overall mechanical properties and the underlay should remain bonded, firm and soft enough for comfort. [9]

Various types and combinations of underlay or carpet cushion as it is referred to in the US exist today. For the purpose of this paper, definitions are in conjunction with BS 5808 [10] where they fall into the following three categories:

1. Fibrous, consist of any type of felt product.
2. Non-Fibrous, is an underlay produced from an elastomeric polymer.
3. A combined underlay is a product produced from a combination of felt and some types of rubber product. [11]

1.2 Use Of Fibrous And Non Fibrous Waste In Underlay

In the last ten years [12] major changes have occurred within the underlay industry. External pressures have been responsible for manufacturers including recycled material in areas of construction and material science. Recycled material used in product ranges consists of natural felt burlap bags, process foam scrap, production waste from manufacture and tyre rubber. Providing appearance retention, underfoot comfort and heat insulation, crumb rubber is highly favoured with producers. Moore [13] describes a carpet underlay comprising a sheet of resiliently deformable polymeric material made from recycled rubber crumb. Various British manufacturers using crumb rubber within their product ranges consist of Gaskells, Duralay and Ratcliffes.

A successful product utilising waste material is process foam scrap. In North America, the process is so successful that the demand for scrap exceeds the supply [14]. Foam particles from various sources such as fabrication scrap and post consumer waste are ground into small pieces and turned into bonded underlay.

2.0 EXPERIMENTAL METHODS

This section of the paper will report on the experimental procedure undertaken to produce the results. The in-house produced samples together with three alternatively sourced commercial grade underlays were tested under a series of routine British Standards. This allowed the in-house specimens to be characterised against the standards of commercial grades.

2.1 In-house Sample Preparation and Equipment Descriptions

A number of feasibility studies were carried out to control parameters, which included the type of binder used, type and quantity of waste, particle size, temperature and dwell times. The studies were separately reviewed and trial samples assessed for potential improvement or elimination. The final choice of specimen includes the following materials and processing techniques.

Electrostatically flocked fibrous waste in the form of selvedge edging obtained from an outside source. The waste was granulated into uniform particle size pieces of ≅ 4mm. The waste material, together with controlled quantities of urethane acrylic co-polymer binder, water and surfactants were mechanically mixed together using a paddle mixer. The mixture was then spread over a polypropylene backing material. The assembly was then subjected to high temperature curing at 160 °C using a stenter (Roaches Extraction Oven).

The sequential steps of producing the in-house samples included the short process of:

Waste obtained from outside source

↓

Granulated into particle size of 4mm

↓

Waste, binder/water, surfactants etc mechanically stirred

↓

Waste evenly spread onto the backing material

↓

Sample cured in stenter

2.2 Specification of Commercial Underlay

Commercial grade underlays were sourced on the following basis:

- Heavy contract graded
- Contained recycled material
- Similar thickness to in-house samples

Table 2.2.1 shows specifications of the commercial grade samples, including the in-house sample.

Table 2.2.1: Specifications of the underlay samples.

Manufacturer	Materials Used In Manufacture	Method Of Production	Classification*	End Use *
A	Foamed rubber crumb on a PP backing	Lamination/ Bonding	Non-Fibrous	Heavy Contract (H/C)
B	Foamed rubber crumb layer, needlepunched layer of jute	Needlepunching Laminating Bonded	Combined	Heavy Contract (H/C)
C	Foamed rubber crumb on a PP backing	Lamination/ Bonding	Non-Fibrous	Heavy Contract (H/C)
IN-HOUSE	Waste flocked carpet particles mixed with binder	Bonded	Combined	Heavy Contract (H/C)

* The underlay type has been classified from the classification on the BS 5808 standard [10].

2.3 BS Test Details

A selected testing programme was conducted on the specimens in accordance with BS 5808 [10]. The testing protocol included Breaking Strength & Elongation, Resistance to Cracking/Breaking, Dynamic Loading and Tear Strength, which is a recognised automotive standard used by manufacturers to assess the underlay for resistance to tear. Specimens were prepared in accordance with standard guidelines. Table 2.3.2 shows the testing specifications of the samples.

Table 2.3.2: Testing specification of the samples.

TEST	STANDARD	APPARATUS	SPECIMEN SIZE	SAMPLES NUMBER	TEST OBJECTIVE	PERFORMANCE REQUIREMENT
Determination of Breaking Strength & Elongation	BS 2576	Instron	20 x 5 cm	5 in each direction i.e. m/c & c/d	Records max force applied in stretching to rupture and corresponding extension of the specimen	Breaking strength 40N minimum.
						Elongation 10% max for applied force of 40N
Resistance to Cracking & Breaking	BS 5808 (app A)	Metal plate (Minimum 8 x 4cm) Weight 2.5kg	24 x 8 cm	3	Folded rectangular piece of underlay where 2.5 kg is placed for 1hr. Specimen is examined for cracks	No cracks longer than 50mm. No cracks in the backing material.
Dynamic Loading	BS 4052 BS 4098	Thickness gauge Dynamic Loading M/C	12.5 x 12.5 cm	3	Loss in thickness after dynamic loading	Max % Thickness loss: fibrous-40%, non fibrous-15%, combined-20%
					Compression after dynamic loading	2mm minimum 7mm maximum
					Work of Compression after dynamic loading	50J/m² minimum 200 J/m² maximum
					Retention of original work of compression	Min per req is 40% retention of original work of compression
Tear Strength	Automotive No 154 (1993)	Instron (Model 102.6)	25 x 5 cm	5 in each direction of m/c & c/d	To stretch the sample until complete rupture occurs	Av. Recorded breaking load in each direction Work of rupture (n.mm) in both directions

3.0 EXPERIMENTAL RESULTS

3.1 Determination of Breaking Strength and Elongation.

Table 3.1.1 shows the mean results for load/ displacement and percentage strain at maximum load for the four specimens.

Table 3.1.1: The results of the breaking strength and elongation of the specimens.

			Displacement At Max.Load (mm)	Load At Max.Load (KN)	Strain At Max. Load (%)
SAMPLE & DIRECTION OF SAMPLE	**Sample B** Machine Direction	Mean	31.62	.1216	15.18
		Standard Deviation	2.18	.0166	1.09
		Cof. Of Var.	6.89 %	13.64%	6.89 %
	Sample B Cross Direction	Mean	32.1	.2176	16.07
		Standard Deviation	3.42	.0182	1.71
		Cof. Of Var.	10.64%	8.35%	10.64%
	Sample A Machine Direction	Mean	40.82	.5939	20.41
		Standard Deviation	1.407	.0194	0.704
		Cof. Of Var.	3.45%	3.26%	3.45%
	Sample A Cross Direction	Mean	46.71	.5076	23.37
		Standard Deviation	2.064	.0494	1.031
		Cof. Of Var.	4.42%	9.73 %	4.42%
	Sample C Machine Direction	Mean	7.13	.6103	3.563
		Standard Deviation	.697	.0427	.349
		Cof. Of Var.	9.79%	6.99 %	9.79%
	Sample C Cross Direction	Mean	9.216	.4785	4.62
		Standard Deviation	0.500	.0584	.2500
		Cof. Of Var.	5.42%	12.20 %	5.42%
	In-house Machine Direction	Mean	75.26	.2068	50.17
		Standard Deviation	22.37	.0419	14.19
		Cof. Of Var.	29.72%	20.28 %	29.72%
	In-house Cross Direction	Mean	74.62	.1863	49.75
		Standard Deviation	19.44	.0290	12.96
		Cof. Of Var.	26.06%	15.57 %	26.06%

Figure 3.1.1 shows a scatter plot of the entire samples relating to load against displacement values.

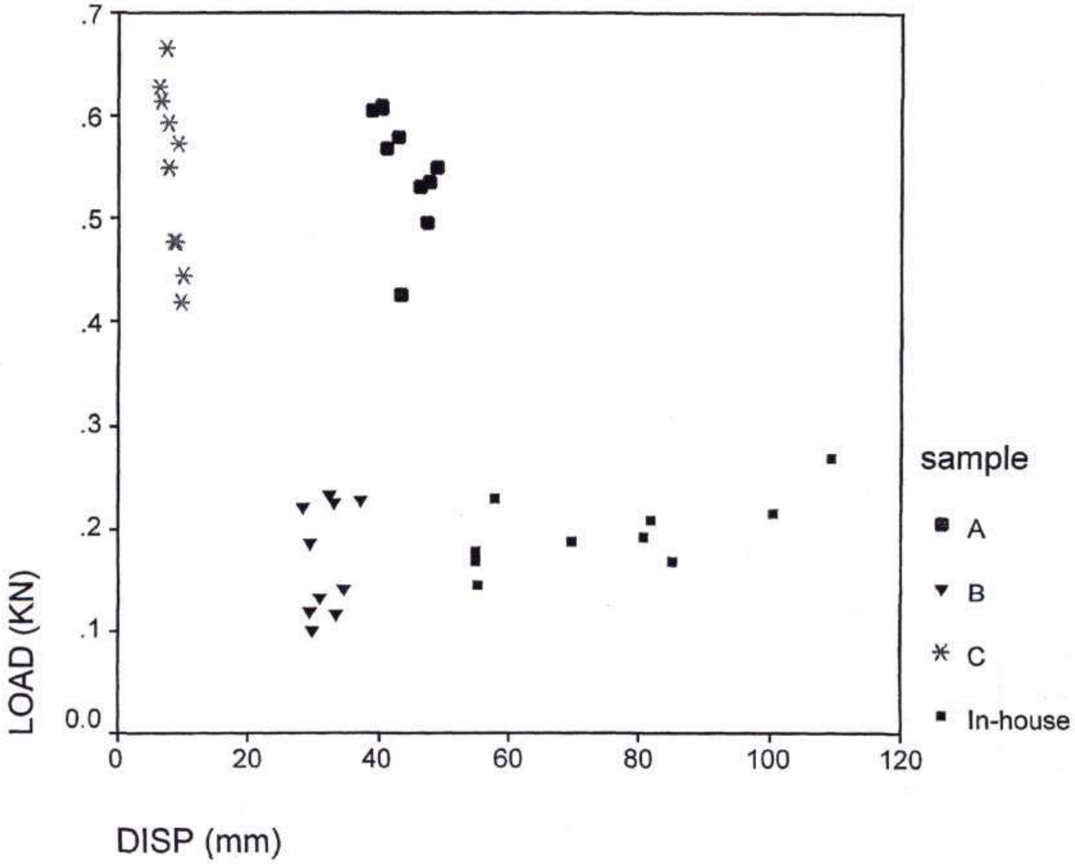


Figure 3.1.1: Load/ Displacement values for samples.

3.1.2 Correlation Coefficients of Load /Displacement

To determine the load/displacement relationships. Correlation coefficients were determined for each sample. Table 3.1.2.2 shows the results.

Table: 3.1.2.2: Correlation values for the samples.

SAMPLE	CORRELATION	SIG. (2-TAILED)
IN-HOUSE	.658*	.038
SAMPLE C	-.828**	.003
SAMPLE B	.269	.453
SAMPLE A	-.537	.110

*Correlation is significant at the 0.05 level (2-tailed)
** Correlation is significant at the 0.01 level (2-tailed)

The results show the correlation was significant for the samples of In-house and sample C. The following two figures show the samples of In-house and sample C with the line of best fit. Linear regression was then used to obtain the equation of the line showing the relationship between the load and displacement.

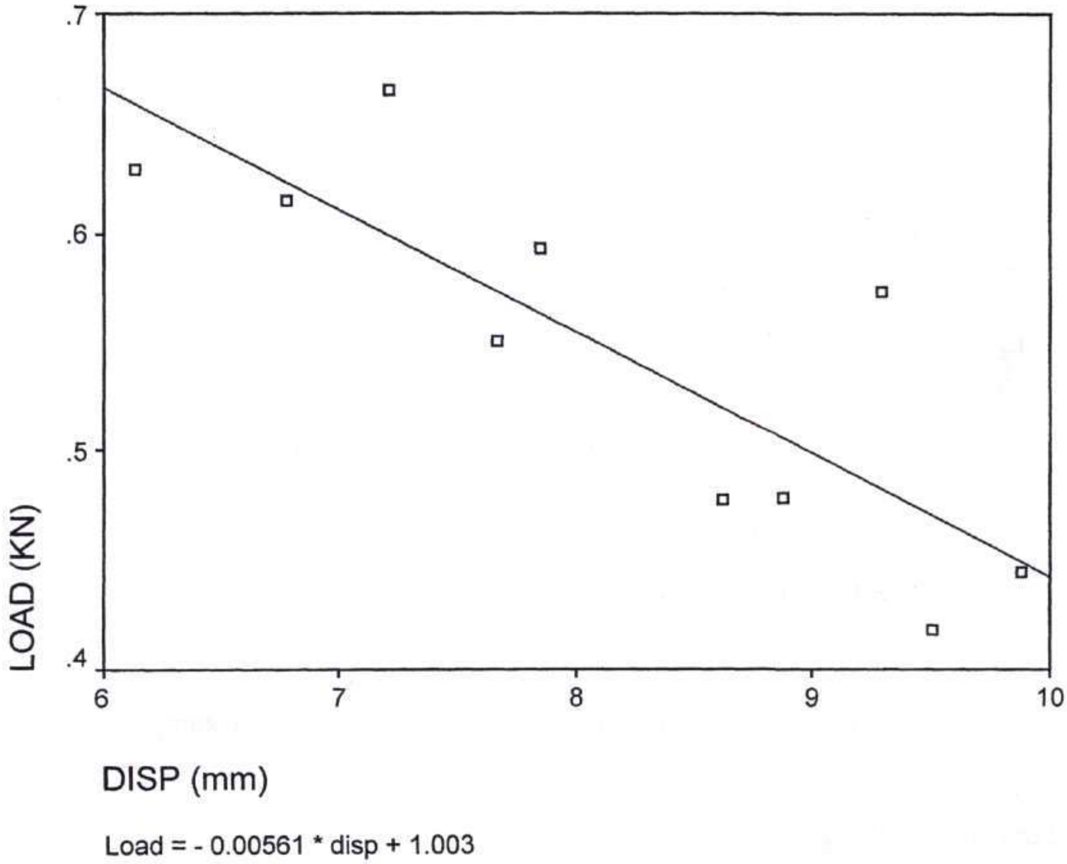


Figure 3.1.2.2: Load /Displacement values for sample C.

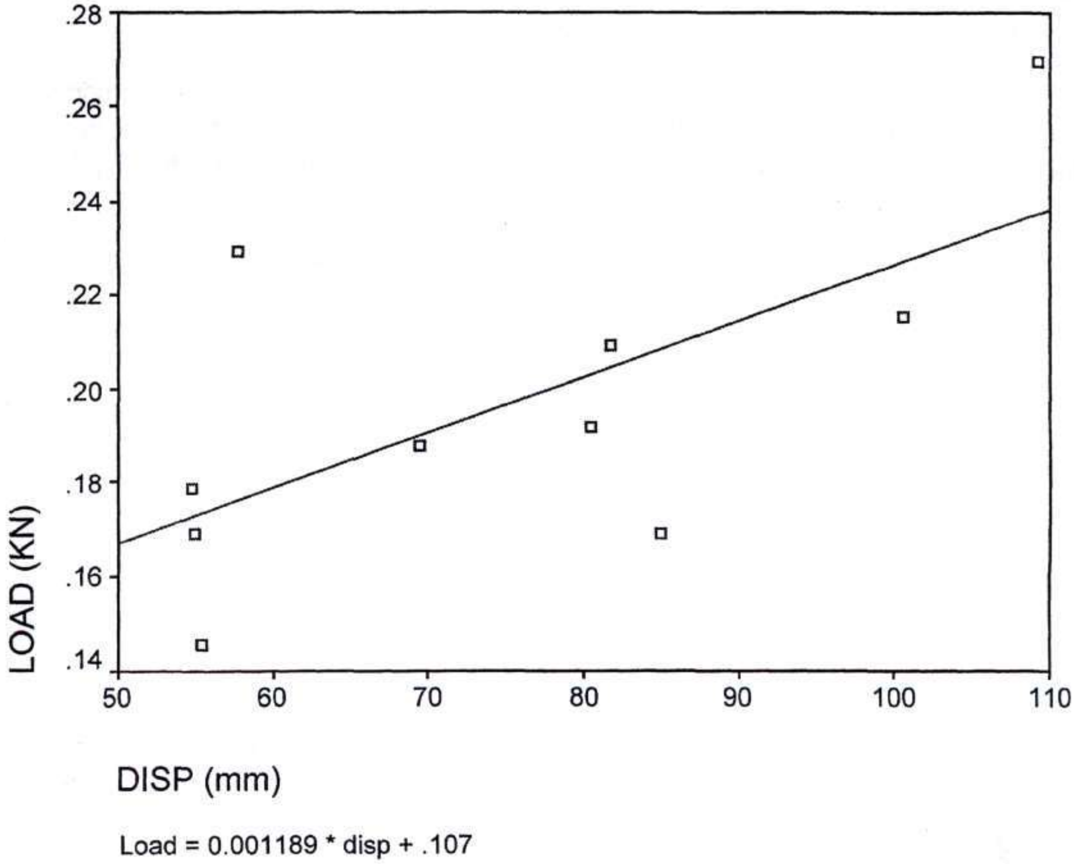


Figure 3.1.2.3: Load/Displacement values for In-house sample.

3.2 Dynamic Loading

3.2.1 Thickness/ Pressure before and after dynamic loading

Table 3.2.1.3 shows the mean recorded values before and after dynamic loading of 1000 cycles for each specimen under different pressure values.

Table 3.2.1: Thickness/Pressure before and after dynamic loading.

PRESSURE (kPa)	BEFORE DYNAMIC LOADING THICKNESS (mm)				AFTER DYNAMIC LOADING THICKNESS (mm)			
	SAMPLE C	SAMPLE A	IN-HOUSE	SAMPLE B	SAMPLE C	SAMPLE A	IN-HOUSE	SAMPLE B
2	6.89	6.50	11.52	10.68	6.74	6.36	11.05	7.32
5	6.73	6.33	11.3	9.93	6.58	6.22	10.90	6.73
10	6.48	6.16	10.95	9.30	6.35	6.02	10.07	6.14
20	6.22	5.85	10.2	8.08	6.04	5.69	9.65	5.52
50	5.49	5.19	9.22	5.90	5.35	4.96	8.83	4.63
100	4.76	4.46	8.4	4.92	4.65	4.27	8.1	4.02

As expected the results indicate the thickness values are higher before dynamic loading than those after loading. A typical thickness curve would show a rapid decrease in initial thickness followed by a decreasing slope until the underlay is compressed to a thickness at maximum pressure. Such curves are used to express mechanical properties of carpet, such as softness and resilience [15]. Figure 3.2.1.4 shows the thickness/ pressure curves for all four specimens.

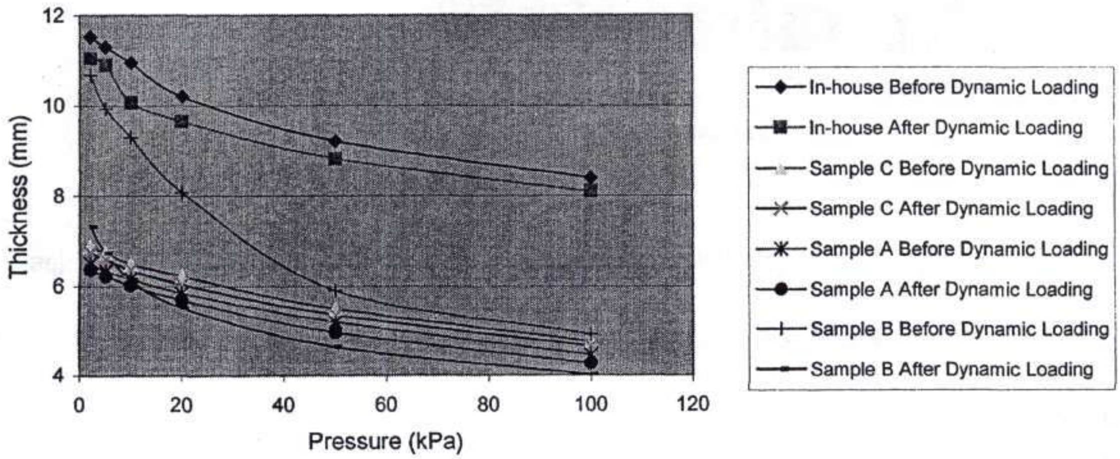


Figure 3.2.1.4: Thickness/ pressure values before and after dynamic loading.

The results show there is a rapid decrease in the initial thickness followed by a decrease in the slope until the specimen is fully compressed at maximum applied pressure. The in-house produced samples have the highest original thickness of all the specimens before dynamic loading and largely maintain this difference after dynamic loading. Both samples A and C show that an increase in pressure does not change the thickness measurements dramatically. However, sample B shows the greatest loss in thickness before and after dynamic loading.

3.2.2 Loss In Thickness After Dynamic Loading of 1000 Cycles

The thickness loss of a textile floor covering is defined as: the difference between the thickness of the textile floor covering, measured under the standard pressure specified, before receiving a number of standard impacts" [16] Figure 3.2.2.5 shows the four specimens and the % loss in thickness. The acceptable values or % loss in thickness for different categories of underlay are as follows.

Non fibrous- 15% max (Samples C & A)
Combined- 20% max (Sample B, In-house)

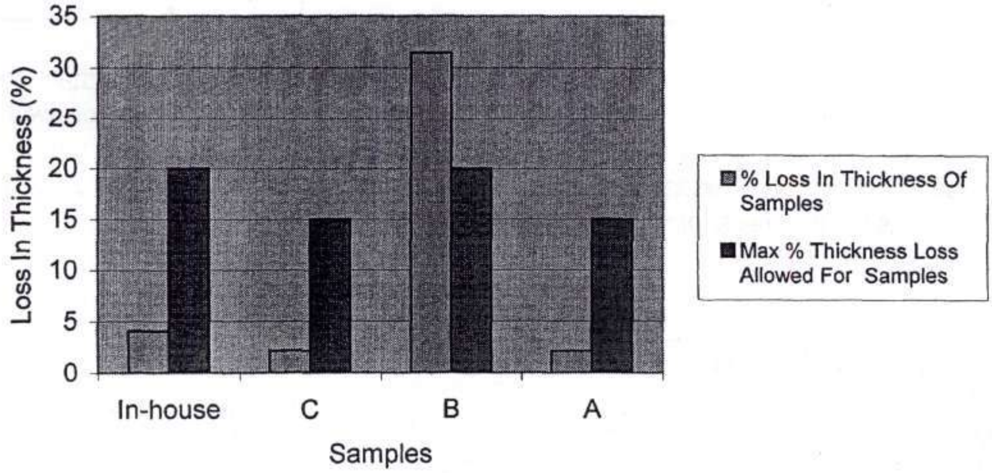


Figure 3.2.2.5: The % loss in thickness after dynamic loading of 1000 cycles.

Samples A and C are well within the 15% loss in thickness permitted by the standard applied and therefore pass. The combined samples consisting of sample B and the In-house sample are allowed upto 20% loss in thickness. From figure 3.2.2.5 sample B clearly fails, but the In-house sample is well within the limits.

3.2.3 Compression

Compression is the difference between the initial thickness and the thickness when compressed to 100 kPa. According to BS 5808 [10] the performance requirement for compression after dynamic loading should be a minimum of 2mm and a maximum of 7mm.

Table 3.2.3.4 shows the compression and the work of compression for each specimen.

Table 3.2.3.4: The mean values for both compression and the work of compression.

SAMPLE	COMPRESSION (mm)	WORK OF COMPRESSION (J/M²)
A	2.09	79.66
C	2.22	81.43
B	3.3	85.71
In-house	2.95	89.95

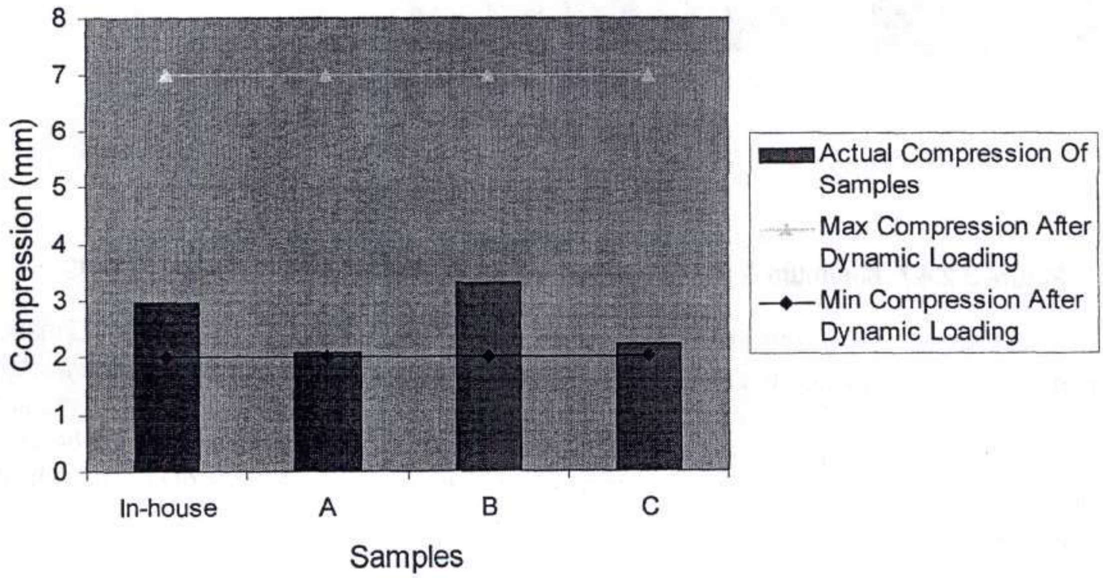


Figure 3.2.3.6: Minimum & Maximum compression after dynamic loading.

Figure 3.2.3.6 shows the specimens are above the minimum of 2mm and below the maximum of 7mm.

3.2.4. Work of Compression

The work of compression is the work done on the floor covering when the pressure is increased from 2kPa to 100kPa. According to BS 5808 [10] the minimum performance requirement is 50 J/m^2 to 200 J/m^2 maximum. As mentioned previously, the total loss in thickness is a way of measuring softness. However, a more useful way of assessing softness is the work of compression, which is calculated from the area under the thickness pressure curve. Figure 3.2.4.7 shows the minimum and maximum work of compression values after dynamic loading.

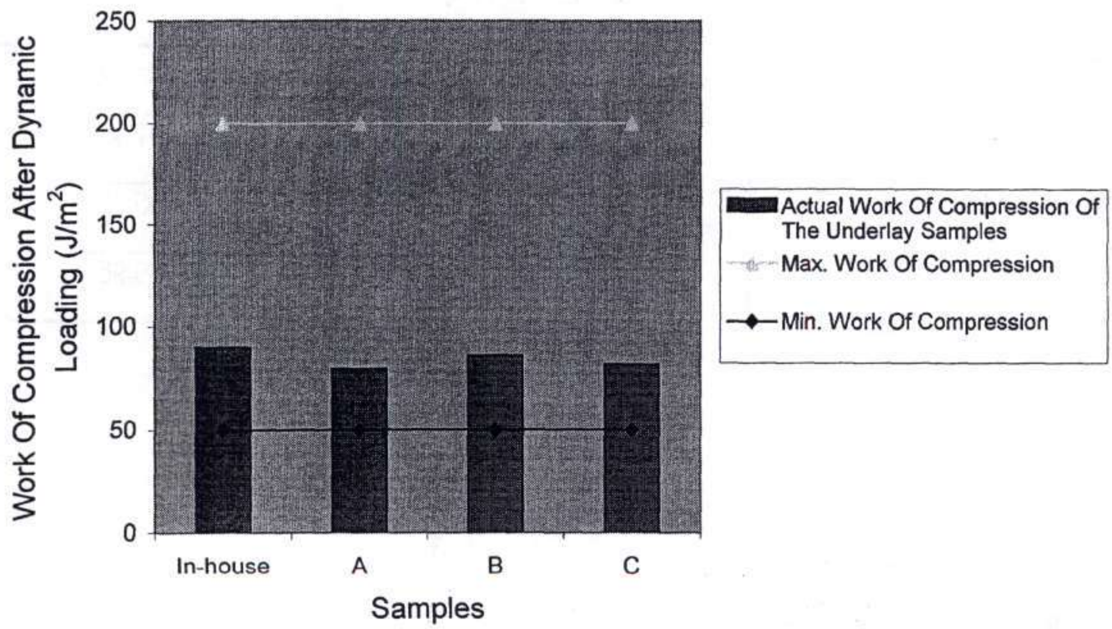
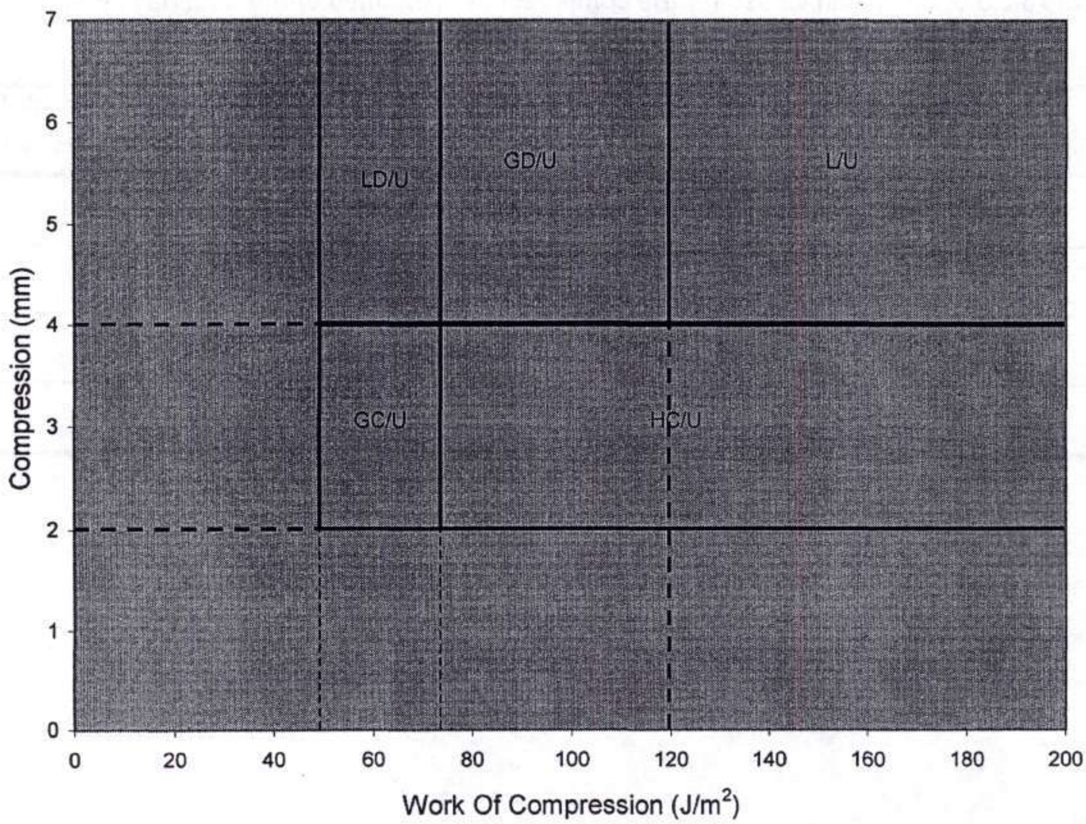


Figure 3.2.4.7: Minimum & maximum work of compression after dynamic loading.

The results show all the specimens are between the minimum and maximum performance requirements. The compression and work of compression are used in conjunction with one another to classify the underlays. In accordance with BS 5808 [10] to achieve the heavy contract grading, the samples must display a compression of between 2–4 mm and a work of compression between 75 and 200 J/m^2. Figure 3.2.4.8 shows a grading scheme in which all categories of underlay should fall into. Manufacturers mainly aim their products at the heavy contract market.



HC/U – Heavy Contract
L/U- Luxury
GC/U – General Contract
LD/U- Luxury Domestic
GD/U- General Domestic

Figure 3.2.4.8: Classification of underlays (in accordance with BS 4098) [15].

3.2.5 Retention of the Original Work of Compression

The following results show the original work of compression. This is calculated as follows, the result is expressed as a percentage (%).

$$\frac{\text{Work of Compression Before Dynamic Loading}}{\text{Work of Compression After Dynamic Loading}} \times 100$$

Table 3.2.5.5 shows the mean compression % retained of the specimens and pass or fail verdict for minimum performance requirement according to BS 5808 [10].

Table 3.2.5.5: The mean values for the compression % retained of the underlay samples.

SAMPLE	COMPRESSION (%)	BS 5808 – Has The Sample Passed The Minimum Requirement Of 40%
In-house	86.32	Yes
C	98.83	Yes
A	99.46	Yes
B	52.48	Yes

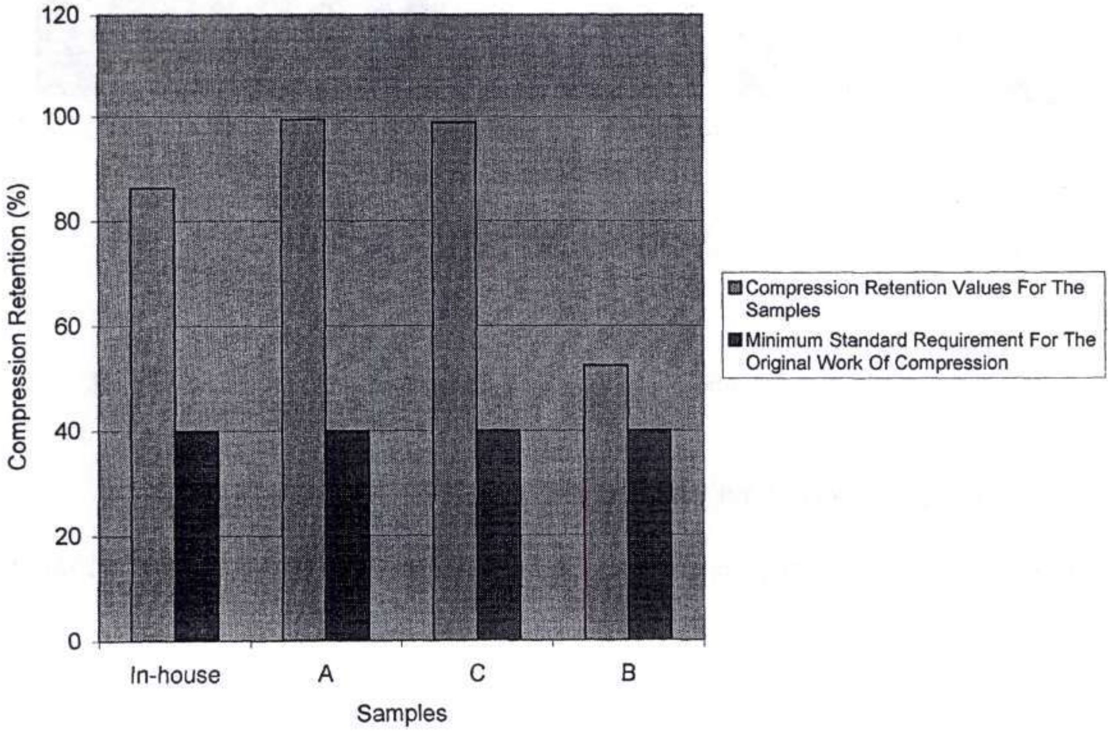


Figure 3.2.5.9: Original work of compression.

Figure 3.2.5.9 shows the minimum requirement for original work of compression is 40%. Sample B barely exceeds the minimum compared to the other samples.

3.3 Resistance to Breaking and Cracking

Table 3.3.6 shows the results for the breaking and cracking of each of the underlay samples.

Table 3.3.6: Results for breaking/ cracking.

		Sample Number		
		1	2	3
SPECIMEN	In-house	No cracks appeared in the sample. However, signs of folding are evident.	No cracks appeared in the sample. However, signs of folding are evident.	No cracks appeared in the sample. However, signs of folding are evident.
	Sample A	No cracks appeared on the backing material. However, there were 2x 5mm cracks on either folds of the crumb layer.	No cracks appeared on the backing material. However, there were two cracks of 3 and 4 mm on either folds of the crumb layer.	No cracks on the backing material. However, there were some holes in the crumb layer down one fold.
	Sample B	The A fold of the crumb rubber there is a slight distortion of the rubber. On the hair side there is visible evidence where it has been folded.	No cracks have appeared on the backing material or in the crumb rubber.	No cracks have appeared on the backing material or in the crumb rubber layer.
	Sample C	No cracks have appeared on the backing material or in the crumb rubber layer.	No cracks have appeared on the backing material or in the crumb rubber layer.	No cracks have appeared on the backing material or in the crumb rubber layer.

The results have shown that all the underlay samples meet the minimum performance requirement stated in BS 5808 [10] showing no signs of cracking or breaking. Including the measurement of the cracks in the support layer, which does not exceed 50 mm in dimension. The sample that did show signs of cracking and breaking was the sample A. Upon analysis, each sample that was tested showed signs of small cracks appearing in the crumb layer. However, approximate sizes of these cracks were no greater than 5mm in length. Samples B, C and In-house displayed excellent resistance to breaking and cracking.

3.4 Resistance To Tear Strength

Table 3.4.7 shows the average load values for the specimens in both directions.

Table 3.4.7: Average load values recorded for the underlay samples.

SAMPLE AND DIRECTION OF SAMPLE		AV. Breaking Load (N)
B CROSS DIRECTION	MEAN	22.49
	STANDARD DEVIATION	8.46
	Cof. Of Var.	38.0%
B MACHINE DIRECTION	MEAN	43.20
	STANDARD DEVIATION	8.52
	Cof. Of Var.	19.95%
IN-HOUSE CROSS DIRECTION	MEAN	70.8
	STANDARD DEVIATION	12.91
	Cof. Of Var.	18.24%
IN-HOUSE MACHINE DIRECTION	MEAN	76.78
	STANDARD DEVIATION	29.58
	Cof. Of Var.	30.52%
C CROSS DIRECTION	MEAN	46.25
	STANDARD DEVIATION	32.87
	Cof. Of Var.	58.24%
C MACHINE DIRECTION	MEAN	48.12
	STANDARD DEVIATION	16.21
	Cof. Of Var.	32.01%
A CROSS DIRECTION	MEAN	148.40
	STANDARD DEVIATION	55.93
	Cof. Of Var.	42.30%
A MACHINE DIRECTION	MEAN	183.45
	STANDARD DEVIATION	31.04
	Cof. Of Var.	17.43%

The above results are expressed graphically in figure 3.4.10, which shows the average breaking load for the machine and cross directions.

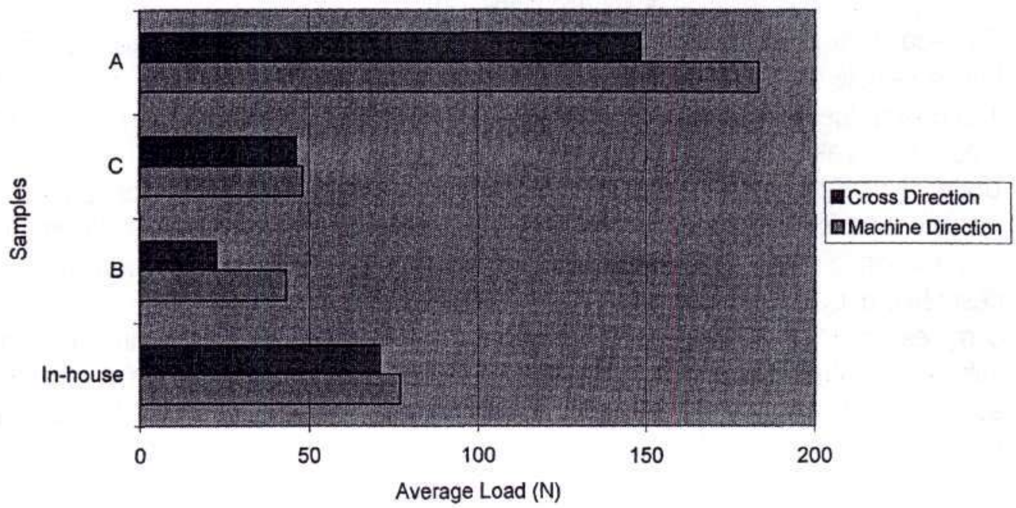


Figure 3.4.10: Average breaking load of samples.

The results show the sample A has the highest breaking load of 183.45 N. Including a significant difference of over 30N between directions. Comparing this to the sample C which has negligible difference of 2N in each direction.

All samples display high coefficient of variance values indicating significant difference in the individual values recorded during the testing procedure. However, this could be due to the small number of samples tested and is expected to drop with increase in number of samples tested.

4.0 DISCUSSION OF RESULTS

Mechanical properties (both static and dynamic) have been analysed. The specimens are compared and correlated on the basis of the breaking strength and elongation, resistance to tear, resistance to breaking and cracking and dynamic loading. These properties are compared according to British Standards.

4.1 In-house Sample

An underlay should have adequate tensile strength [17]. The in-house sample displays reasonable tensile properties comparable to sample B. The load/displacement values obtained during the course of the investigation show the correlation coefficient of 0.658. Linear regression was used to determine the equation of the line.

Load = 0.001189 * disp + 1.07

Relating poor performance of In-house sample compared to samples A and C could be due to the following:

- The sample is produced in-house and not commercially.

- Slight uneven spread of the waste particles could create weaker areas.

Using a more resilient polypropylene carrier fabric and improving waste particle spreading technique could improve these shortcomings.

Romageon [18] recommends underlays should incorporate excellent antislip properties. The in-house sample displays this property by way in which the waste particles adhere to one another. Throughout the testing regime for cracking/breaking the samples showed no signs of breaking or cracking indicating excellent resistance.

Under dynamic conditions the in-house samples perform excellently. The sample has met the maximum performance requirement for percentage thickness, therefore displaying good softness and resilience properties. An independent study has shown a high work of compression is desirable, but a value over 750 J/m^2 for an assembly is considered too soft for comfort, as is compression greater than 12mm [19]. All the samples tested including the in-house sample display values lower than this hence can be classified as not too soft. The sample would improve comfort as it has a high work of compression, which is one of the dominant factors to extend wear life and reduce thickness loss of the carpet.

4.2 Sample A

This sample has high load and low displacement values indicating excellent tensile properties. Despite having good tensile properties the sample performs poorly under dynamic conditions. The work of compression is also very low for this underlay. The percentage thickness retention is low, hence comfort is lower compared to other samples.

The sample has poor resistance to cracking. This is due to the high crumb rubber to latex ratio. This results in inadequate binding of the crumb by the latex and hence cracking occurs.

4.3 Sample C

This sample displays reasonably high tensile strength with moderate elongation and equally balanced tear resistance in either direction. The load/displacement values obtained during the course of the testing regime have shown a correlation coefficient with the negative correlation value of - 0.828. Further investigation using linear regression has shown a positive relationship exists between values of load and displacement displayed by line equation

Load = - 0.00561* disp + 1.003

The sample can take maximum load with minimum displacement and a high work of rupture indicating the sample is strong and has a high resistance to tear. The sample has good thickness qualities, as the change in thickness for before and after dynamic loading is negligible when a load is applied. The compression and work of compression values are low therefore the sample only just makes the heavy contract grading.

4.4 Sample B

Sample B displays tensile properties comparable to the in-house sample. However, there is no significant correlation in the results to indicate a positive relationship between the load and displacement values. However, previous testing of this sample reveals a high work of rupture showing the sample has a high resistance to tear. Reasons for this behaviour could be due to combined crumb layer and the needlefelted layer supporting it.

The results from the dynamic loading trials have shown the underlay sample has the poorest qualities, displaying the greatest loss in thickness before and after dynamic loading. A previous study [20] highlights a similar product to sample B portraying a high loss in thickness after dynamic loading

However, the values for the compression and work of compression are the second highest after the In-house sample showing the sample meets the heavy contract grading with ease. The felt/crumb underlay has reasonable tensile properties and good resistance to tear. Theoretically this should be the best type of underlay to choose for application due to the advantage of the crumb rubber with its compact nature and compressible properties.

5.0 CONCLUSIONS & FURTHER WORK

Not one specific type of underlay is suitable for all types of installation, therefore careful consideration should be given to the requirements of the underlay. From the results of the various tests, it can be seen that samples A and C display excellent tensile and tear properties and poorer dynamic qualities. Whereas, the In-house sample and sample B display lower tensile and tear qualities, but have stronger dynamic properties and display a greater resistance to cracking.

Further work on the In-house sample will include improvement in backing material followed by period trials on light and heavy traffic areas to examine residual properties. Effect of underlay thickness and carrier on performance characteristics of the sample will be systematically examined according to British Standards. Based on data generated from this exercise, a mathematical model will be developed to allow selection and performance characteristics of a given underlay.

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